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**14. ABSTRACT**
We have made significant progress towards the computation of underwater shocks. We have used state-of-the-art numerical technology, largely developed by us, including the level set method, ghost fluid method, ENO and WENO shock capturing schemes, solid fluid interaction methodology and the fast closest point transform. We use Eulerian methods to model the detonation wave and the fluid flow and Lagrangian methods to compute the dynamic response of solid targets. Our main success so far comes in the very accurate fluid/solid interaction using our mixed scheme. We have also developed a new, higher order fast closest point transform and a module which integrates the level set method with the ghost fluid method to deal with the multiphase gas boundary. We are developing a module coupling these methods to compute reacting fluid interfaces.

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# Fourth Quarterly Report

In fulfillment of STTR contract # N00014-01-M-0237

# Level Set and Ghost Fluid Based Underwater Shock Analysis

Level Set Systems, Inc

January 13, 2002

## 1. Introduction

Level Set Systems, Inc (LSS) and Caltech personnel have continued their collaboration, using recently developed numerical technology to compute detonation phenomena in order to accurately deal with mixed phase flow, high strain rate solid mechanics and complex geometry. These new techniques, developed largely by this personnel and consultants, include the level set method, ghost fluid method, ENO and WENO shock capturing schemes, solid-fluid interaction, and the fast closest point transform. We have begun to use these and other novel AMR and multiresolution gridding techniques to develop and implement an advanced fluid modeling capability for use in underwater shock analysis to support design optimization of ship and submarine hull structures.

## 2 Mixed phase flow

The fluid flow which impinges on the solid hull is highly complex. Typically the detonation produces a shock wave and gas bubble which then interact very strongly with the surrounding fluid to produce the loading on the ship hull. In order to accurately capture such phenomena, it is necessary to be able to compute the evolution of the mixed phase flow in the presence of shock waves. Methods based on a Lagrangian formulation have the advantage that they can naturally track material interfaces provided that no change of phase occurs across the interphase boundary, but these suffer from difficulties caused by strong mesh deformation. Purely Eulerian approaches do not suffer from mesh deformation difficulties and it then becomes possible and potentially very effective to apply modern shock capturing techniques. However, Eulerian approaches require the modeling of the various interphase boundaries (gas-fluid or fluid-solid) as mixed cells in which fractions of both phases are present in a given Eulerian mesh cell. The two phases generally differ markedly in their thermodynamic properties and this has historically presented severe difficulties.

The solid-fluid interaction methodology we are developing uses Eulerian methods to model the detonation wave and Lagrangian solid mechanics to compute the dynamic response of the solid targets. The Eulerian capability uses a standard Cartesian mesh, while the Lagrangian solid mechanics code utilizes tetrahedral meshes. Thus, we must couple two disparate algorithms and mesh structures. This is where our innovative algorithms play key roles. The Eulerian mesh covers part of the solid Lagrangian mesh. Level set methodology is used to keep track of the Lagrangian solid boundary via a fast algorithm devised at Caltech. We have begun to develop a new, higher order fast closest point transform. At each step it becomes necessary to take a given solid surface which consists of a collection of faces (triangles) from a tetrahedral mesh. This is called a B-rep. From this surface we need to compute the level set function onto the Eulerian mesh. This was done earlier at Caltech using a fast eikonal solver and some computational geometry. LSS has developed a related, but higher order accurate fast method to do this. We are currently building a module to add to the existing code.

Once this is done, it is easy to identify which Eulerian cells are either purely in the fluid, purely in the solid or overlaying the solid-fluid interface. Using the surface normals provided from the level set it is easy to build a band of Eulerian cells which cover the solid -fluid interface and partly penetrate the solid. This is the ghost fluid region. In these cells special thermodynamic data (ghost fluid data) is placed so that the solid loading can be communicated to the fluid. At the same time the loading from the fluid onto the solid can be calculated by computing traction forces on the interface-the zero contour of the level set (actually the signed distance) function. Again, our new work here involves a higher order fast distance update.

We have also begun to employ the ghost fluid concept in order to compute the fluid mechanics capability in order to compute the fluid mechanics associated with the detonation of an underwater explosive charge. We have written a module which applies and integrates the level set approach together with the ghost fluid method (GFM) to deal with the multiphase gas fluid boundary. The current report demonstrates successful computations obtained by this new approach.

The GFM was developed first for nonreacting fluid interfaces. In a simple Eulerian fashion the technique enables one to keep the density as a Heaviside function with no spurious smearing or oscillations. Basic numerical methodology, devised for high order essentially nonoscillatory single phase flow problems, can be easily extended to cover the multiphase case, even in the presence of drastically different physics. LSS has built a GFM module involving the level set method and GFM to compute nonreacting fluid interfaces. This will soon be integrated into the code we are developing under this program.

LSS is also developing a module, based on the work of Fedkiw (our consultant) Aslam and Xu, extending the GFM to treat multimaterial interfaces where the interface velocity includes the effect of chemical reactions converting one material into another. Again, we shall incorporate this into our new code.

We have also taken some preliminary steps toward the development of a multiresolution adaptive mesh refinement module.

## Results

We have tested our Eulerian / Lagrangian code for the problem with a much more complicated geometry. Consider the domain [0, 1]x[0, 0.75] divided into three regions containing different fluids. Figure 1 below shows the initial setting for our calculation. The regions 1 and 3 are modeled with Lagrangian meshes and the region 2 is modeled with an Eulerian mesh. We compute a right going shock wave initially located at x $= 0.05m$ with post shock state of density $= 4.333 kg/m^3$, pressure $= 1.5 \times 10^6 Pa$ and x_velocity = $328.17\sqrt{10}$. Figure 2 shows the density profile at t = 0.0 and t = 0.0004 seconds respectively. Figure 3 shows the interface location and vector computed at t = 0.0 and t = 0.0004 seconds respectively.

**INITIAL DATA FOR CALCULATION**

final time = 0.0004

x_velocity = 0, y_velocity = 0, pressure $= 1\times10^5\,Pa$

In region 1 and region 3:

$$\gamma = 1.249, \quad \rho = 3.1538 kg/m^3$$

In region 2:

$$\gamma = 1.4, \quad \rho = 1 kg/m^3$$

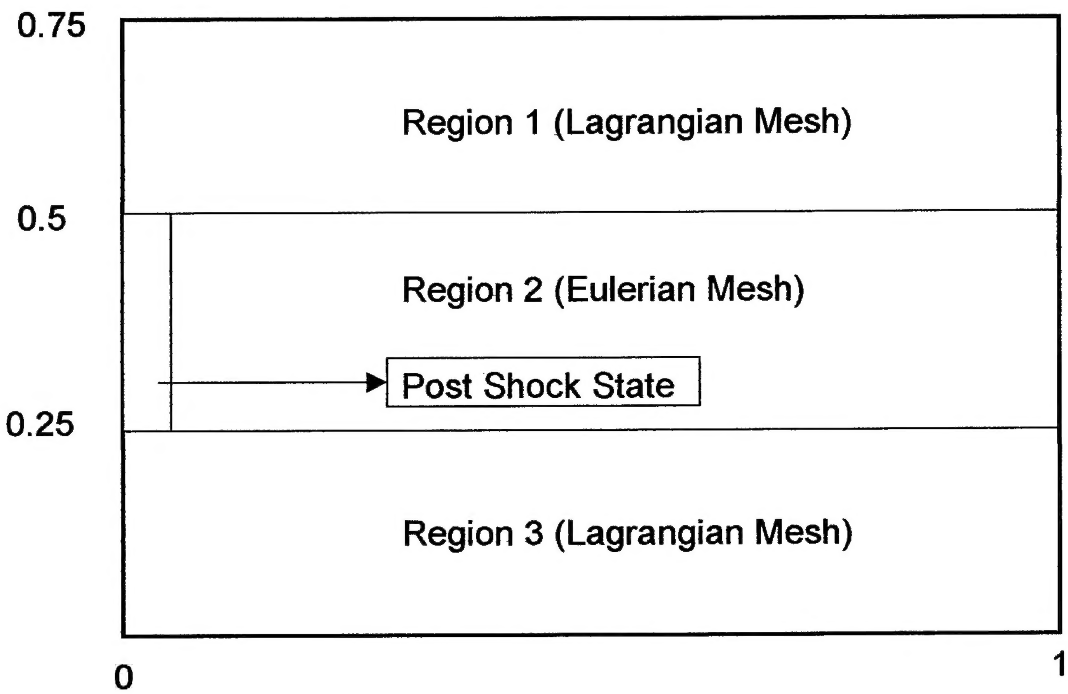


**Figure 1**

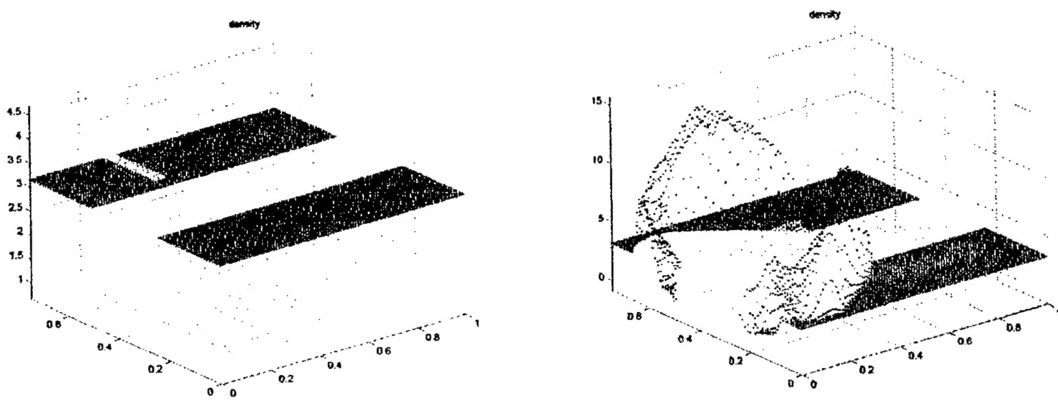


Figure 2

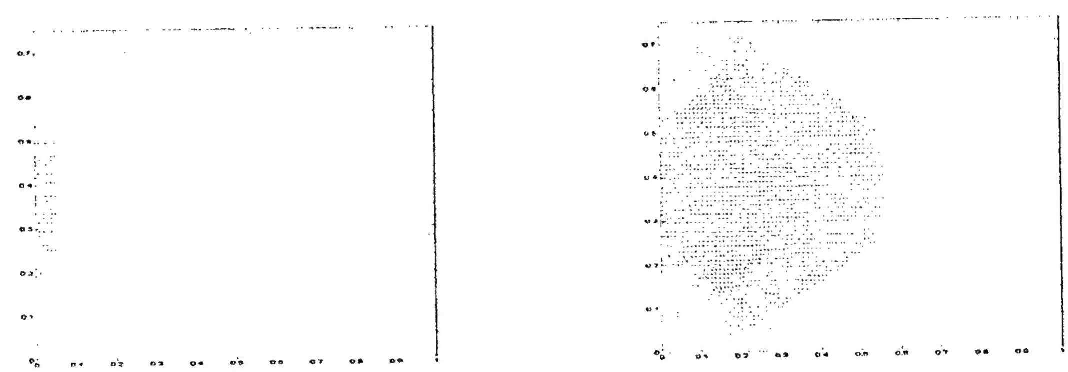

Figure 3